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14. ABSTRACT

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RESPONDING TO F-14 FLEET RUDDER HARDOVER INCIDENTS

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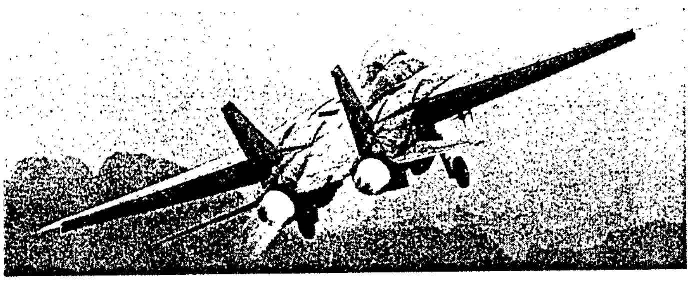

ABSTRACT

Since the summer of 2000, the F-14 community has experienced three occurrences of rudder hardover. The Naval Air Systems Command F-14 test and management teams commenced an investigation into the causes of the failure. This investigation led to the development of rudder hardover emergency procedures for the F-14 aircrews. To assist in developing and evaluating the emergency procedures, the team utilized the F-14 simulation model in the Manned Flight Simulator (MFS) at Naval Air Warfare Center Aircraft Division, Patuxent River, Maryland. Flight fidelity was checked using qualitative comments from an F-14 fleet pilot who experienced the rudder hardover failure in flight and subsequently safely recovered the airplane. A flight test effort was deemed prohibitive due to safety concerns, cost, and the immediate need for NATOPS/PCL procedures required by the fleet squadrons. One challenge in using the simulation was that the resident MFS F-14 aerodynamic model had some limitations that had to be understood when performing tests on these malfunctions. The resultant rudder hardover simulation malfunctions were recently inserted into the F-14 Operational Flight Trainers (OFT's) and are currently being used to train fleet F-14 pilots to handle this emergency situation.

INTRODUCTION

On occasion a flight test organization is required to solve a problem with constraints that prevent the use of traditional flight tests. One such case was the F-14 rudder hardover problem. Three rudder hardovers were experienced in the fleet over a short period of time with one of them contributing to the loss of an aircraft. Due to the severity of the problem, a decision on what actions to take to prevent a recurrence had to be made in short order. Complicating the decision was the fact that an F-14 squadron was returning from deployment and desired permission to continue flying their jets to maintain currency until they could be flown off the carrier to their home base. If the jets could not be flown off, they would be confined to the carrier once it reached port and could no longer conduct flight operations. This would have required craning off an entire squadron of aircraft, a very costly and time-consuming undertaking. The time pressures and the complexity of safely flight testing a rudder hardover made it essential to consider other methods of investigating the problem. Ultimately a recommendation was made based on a combination of analysis and piloted simulation. This process required careful consideration of the limitations of these methods, and the accuracy of the results.

DESCRIPTION OF THE FAILURE

The most recent rudder hardover incident occurred in January 2001. While flying an Air Combat Maneuvering (ACM) flight, an aircrew encountered flight-side hydraulic loss in a right break turn. Calling a "knock-it-off" and attempting to roll wings level, the aircraft was sluggish to respond and continued to yaw right. At this point the aircrew realized there was a problem with the rudders. The failure consisted of a left rudder fully deflected inboard with the right rudder restricted to zero degrees opposing the failed rudder. The aircrew safely recovered the aircraft at the field (without any procedures delineated in Naval Air Training & Operating Procedures Standardization (NATOPS)), but upon a successful arrested landing, the divergent forces caused the aircraft to depart the runway.

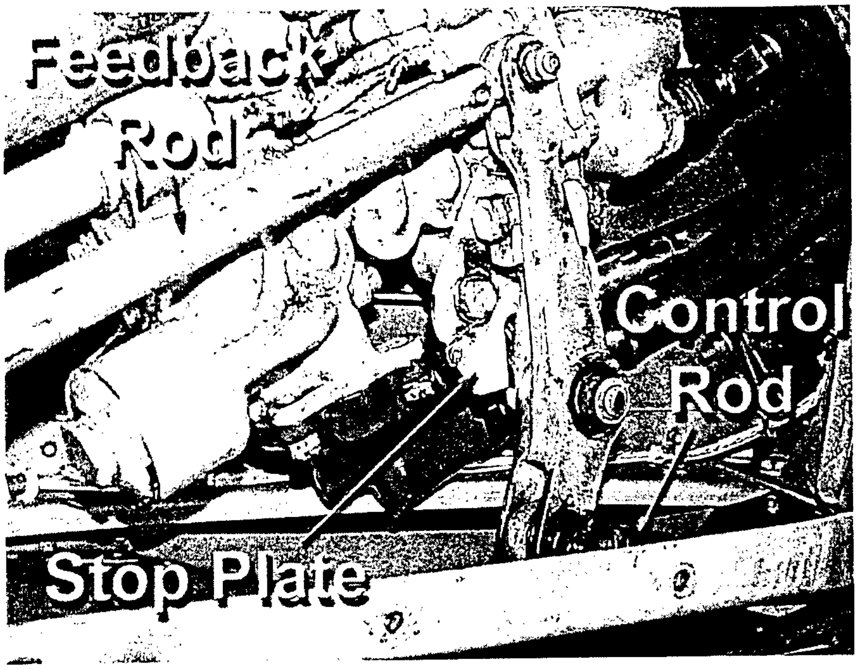

Figure 1: Rudder Stop Plate Installation

Post-flight examination of the aircraft revealed that the problem was due to the mechanical failure of a stop plate attached to the rudder actuator (Figure 1). The stop plate serves the dual functions of limiting servo valve motion, and retaining the seal for a flight hydraulic return passage. Consequently, failure of the stop plate resulted in a hardover of the affected rudder (due to unrestricted servo valve motion) and rapid loss of fluid from the flight hydraulic system (due to loss of the return passage seal). The actual hardover was limited to one of the rudders. However, due to an attendant restriction of control rod motion, the throw of the "good" rudder could be restricted to varying degrees (Figure 2). The worst case restriction of the "good" rudder allowed full throw in the same direction as the hardover and nearly zero throw in the opposite direction. The best case scenario resulted in full throw available in either direction for the "good" rudder. The actual failure on the aircraft could result in any situation between these two extremes.

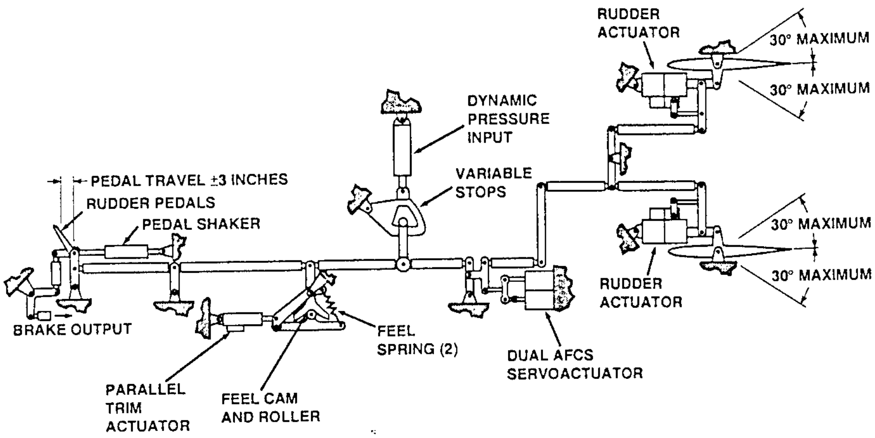

Figure 2: F-14 Rudder Control System

OPTIONS/DECISIONS

The rudder hardover occurrences were considered to be very serious safety-of-flight concerns to the F-14 fleet community and NAVAIR. Carrier-based blue water ops (those flight operations which occur when there is no suitable land-based divert from the carrier) were prohibited via a Red Stripe message from NAVAIR. The Pax River team was requested to support very-quick-response temporary NATOPS flight manual procedures to be promulgated by NAVAIR in case of any future rudder hardover incidents before an in-depth Engineering Investigation could be performed and "hardware" fixes to the problem could be fielded. These procedures also supported a one time only waiver of the Red Stripe limitation to allow the pilots of the returning squadron to fly their jets home. The fly-off was conducted within range of a divert field. The long lead time, high technical risk, and cost prohibitive nature of a flight test program, led the test team to consider the F-14 simulator at Manned Flight Simulator (MFS) the only viable alternative.

The first priority was to ascertain whether the flying qualities of the simulator were similar to those encountered in flight. Eight days after the most recent incident, the incident pilot flew the F-14 simulation with a rudder hardover inserted, at NAS Patuxent River, MD. His comments reinforced the team's prediction that the flying qualities of the simulator were similar to those encountered in flight, although it was slightly easier to fly than the aircraft. The importance of these pilot comments cannot be overstated, as this was the first actual data gathered by the test team. In addition, the team now had validation from a rudder hardover "survivor" that the simulation would be adequate to use in the investigation.

With the knowledge that the simulation was able to support an investigation, the test team considered test options. Usually, the preferred course of action would be to go to flight test. This option was strongly considered. However, it had several drawbacks. First, modifying an F-14 aircraft to insert a rudder hardover failure would be very technically challenging. The failure would have to be inserted and then quickly removed to allow the aircraft to be rapidly brought back to its normal configuration in the event of loss of control. The malfunction insertion also had to be tolerant of second failures, such as loss of an engine. These objectives would have been very difficult to achieve, especially in the short timeframe required to investigate these incidents. Estimates indicated that it would require nine to twelve months to modify an F-14 aircraft for flight test. Furthermore, a flight test effort would have also been cost prohibitive. As a result of these restrictions, the team decided against an actual flight test program.

After reviewing the incident pilot's comments and recommendations, the team began to assemble a test matrix for the simulator test periods. The team felt that the simulation tests had to cover a hardover occurrence in both up and away and power approach (PA) or landing flight phases. Since the failure could result in 0 to 30 degrees of opposing rudder, the team decided on failures with 30, 9.5, and 0 degrees of opposing rudder. To mimic actual flight conditions, the team also decided to vary the failing rudder (left or right) and the direction (inboard or outboard) of failure. This provided some element of surprise for the pilot. The team felt that early recognition of the failure was important. Because of the design of the system, the rudder actuator stop plate failures always result in a flight side hydraulics failure. The stop plate retains a seal, which allows the fluid to be ported out of the actuator, when the plate is gone. The crew also must secure the hydraulic bi-directional transfer pump very soon after the failure or the failure will continue on to a combined side failure resulting in a dual hydraulic failure and probable loss of the aircraft.

F-14 SIMULATION MODEL MAKEUP/LIMITATIONS

The F-14 MFS facilities consist of an F-14D cockpit (front seat), F-14 simulation model (both TF30 and F110 engine models and Digital Flight Control System (DFCS)), lab station, and visual system. The F-14 DFCS Flight-Hardware-In-The-Loop-System (FHILS) containing Operational Flight Program (OFP) 4.4 with actual flight hardware digital flight control computers (DFCC's) was also used during this evaluation. This simulation has been extensively utilized in the past for DFCS development, flight test rehearsal, and mishap recreation. It has been an invaluable tool as long as the simulation strengths and weaknesses are well understood. This is important, as it is very easy to misinterpret

results, especially if they occur in areas out of the simulation database or in areas either estimated or not fully modeled.

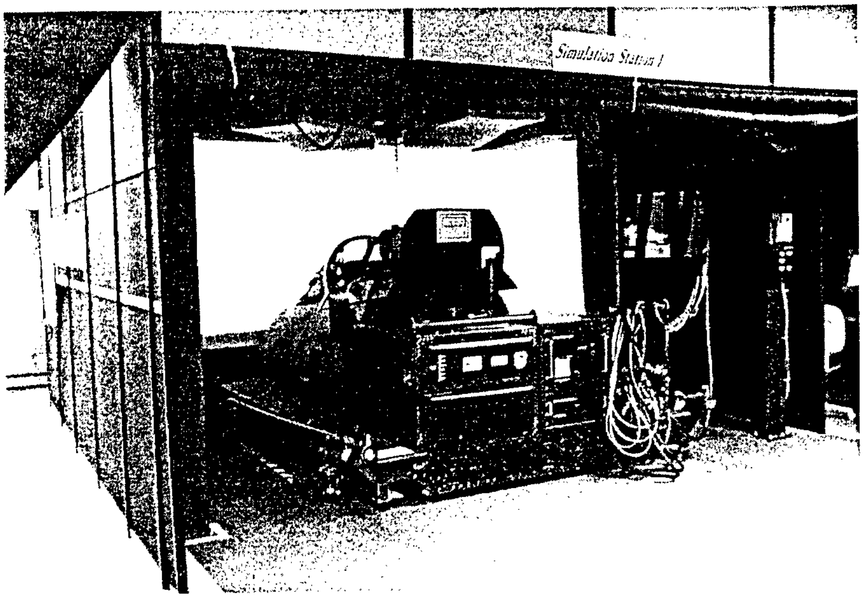

Figure 3: F-14 Cockpit in Lab Station

The MFS F-14 simulation has excellent flight fidelity in both the heart of the envelope for cruise configuration as well as high AOA and power approach configurations. The FHILS version permits great flexibility in selecting and implementing malfunctions. The user can select between either the TF30 or F110 engine variants and between the clean (no stores) or "2x4" (2 AIM-7/9 missiles on the pylons, 2 AIM-54 missiles on the forward tunnel stations, and 2 external tanks) loadings.

The rudder hardover failure scenario was modeled by modifying the MFS F-14 simulation model software. The combined rudder control derivatives were split evenly between the left and right rudders instead of being combined in a single term. This permitted the model to view each rudder independently. Any hardover failure could be selected, partial to full hardover (left or right rudder, inboard or outboard), full to zero opposing rudder, and with or without a flight hydraulic failure. It should be noted that only three of the normal six coefficients were modeled as a function of rudder deflection. Those are the coefficients for roll moment, yaw moment, and side force. The coefficients for pitch moment, axial force, and normal force are not modeled. These three coefficients are second order effects.

The simulation does have some modeling weaknesses and these must be understood within the scope of our tests. First, sideslip angle based upon flight test and wind tunnel data is only modeled out to 20 deg for up and away (gear up) flight and 10 deg for power approach (PA - gear down) flight. Beyond the model data limits, sideslip is linearly estimated based upon the slope at each model's limit.

The F-14 MFS flight fidelity resides in two loadings, clean and a "2x4" loadout. The simulation models were derived from flight test data, mostly in these loadings. Therefore, the resultant flight fidelity is highest in these loadings, which are the only ones used for F-14 testing at MFS. Test teams usually either target one of the loadings which is closest to the desired test loading or they test both loadings and bracket the test results.

The aerodynamic models are divided into several sections, each of which has its own unique characteristics (Figure 4). For example, the high AOA portion assumes the maneuver devices are deployed, as they would be in the actual aircraft in this flight regime. Therefore, a hard wing (flaps/slats retracted) high AOA configuration is not part of this section of the model. Another example is the PA portion of the model, which does not contain maneuver flaps data, only flaps up or full down. This directly affected our tests. The incident pilot utilized maneuver flaps to land his airplane with the rudder hardover. The closest we could test in the simulator was to use both flaps full down and full up and bracket the results.

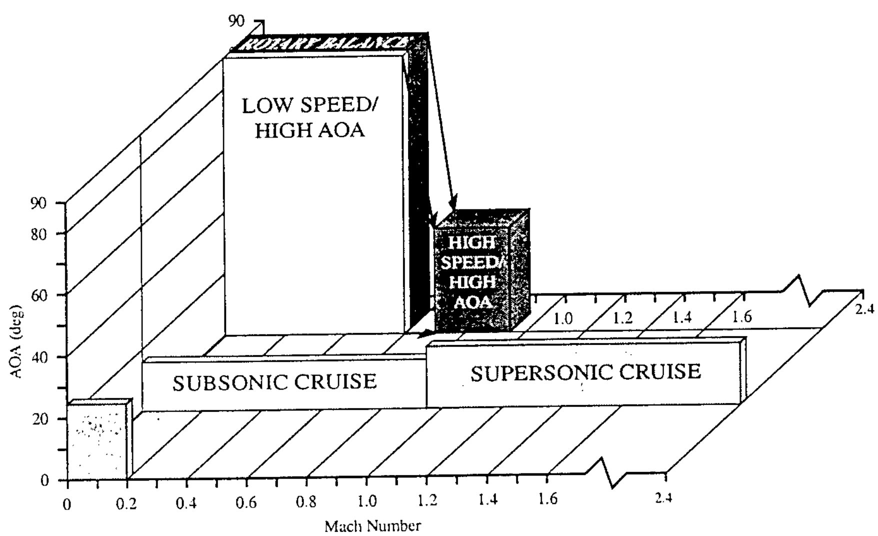

Figure 4: MFS F-14 Database Structure

The landing gear model is a high fidelity model, but has never been validated or thoroughly tested. The shipboard arresting gear models were designed to stop the simulated aircraft in the correct distance, yet did not take into account the re-centering capabilities of actual arresting gear aboard aircraft carriers. An arrested landing would result anytime the aircraft touched down within the landing area. In the real world, the dynamics of the aircraft coupled with the ship's own motion would prevent this from occurring with such regularity. Combine this with the fact that the arrestment model on the ship did not have re-centering capability then the drift in the landing area cannot be assessed. Additionally, the shore-based arresting models were not functional during these tests. Therefore, although there is no dispute that the aircraft with a rudder hardover could depart the runway after a shore-based arrestment, the exact parameters of such an arrestment could not be predicted by the simulation. Thus, our tests were designed to provide as close an answer as possible given the known weak areas of the MFS simulation.

The "2x4" loading was utilized for this evaluation since the incident pilot felt it most accurately represented his incident. It should be noted that the actual physical motion cues a pilot would feel in the aircraft were not present in the simulator.

SIMULATOR TESTS

Simulator tests encompassed four test periods between 12 February and 1 March 2001. Areas covered included reactions to up and away rudder hardover failures including pilot reaction and steps needed to recover the airplane. The team also examined the transition from recovery to the controllability check. PA configuration rudder hardovers at low altitudes with both flaps up and down were also tested leading to shore-based and shipboard approaches and landings. These included arrested landings, waveoffs, and bolters. Both TF30 and F110 engine models were tested. The TF30 model was assumed to be worst case (i.e., slower engine response and less thrust to oppose the rudder hardover). Three opposing rudder configurations were tested; full opposing rudder, 9.5 deg opposing rudder, and no opposing rudder.

UP AND AWAY RESULTS

Upon insertion of a failure, the aircraft immediately rolled and yawed in the direction of the hardover rudder. The pilot's initial reaction was to counter with lateral stick and rudder. If full opposing rudder was available, this returned the aircraft to balanced flight. With little or no opposing rudder, the pilot was able to retain control although with significant sideslip. Differential thrust was then required to restore balanced flight.

The detailed simulator results from the up and away tests are summarized below:

1. In Up and Away flight, the aircraft was always recoverable regardless of the airspeeds tested (< 250 KIAS to > 500 KIAS).

2. Failure at high AOA and high G flight conditions resulted in departures leading to as much as 7,000 to 8,000 ft of altitude loss when no opposing rudder was available (worst case).

3. Use of differential thrust during up and away flight greatly aided the pilot by reducing his workload and the control forces required to maintain balanced or wings level flight. This also reduced lateral stick requirements and placed the stick closer to center allowing for more roll authority if required.

4. With high yaw rates and large uncommanded yaw inputs, the TF30-P414A as installed in the F-14A aircraft may experience compressor stalls leading to engine shutdown preventing the use of differential thrust.

5. Technique – In order to quickly determine which throttle needed to be advanced, it was found that whatever rudder pedal was required to counter the uncommanded yaw, instinctively advancing the opposite throttle and retarding the other throttle to flight idle resulted in error-free application of differential thrust. This simple technique ensured the pilot did not make the situation unrecoverable by advancing the wrong throttle.

POWER APPROACH (PA) RESULTS

A rudder hardover failure in the PA configuration resulted in a departure from controlled flight with an altitude loss of greater than 1,000 ft unless the pilot rapidly applied differential thrust with rudder and lateral stick. If the failure occurred in up and away flight, the transition to the PA configuration was controllable.

The detailed simulator results from the PA configuration tests are summarized below.

1. Unlike up and away flight, the aircraft with a full rudder hardover is not always controllable (specifically during full

flap bolter/waveoff simulations aboard ship), and staying within the ejection envelope within the first few seconds was often impossible.

2. Approaches with full flaps resulted in lightly damped lateral/directional oscillations. No flap approaches were easier to fly; however, airspeed control was difficult. If not monitored constantly, the use of differential thrust caused approach airspeeds to increase above acceptable limits. This was worse with the increased thrust provided by the F110 engines. Although we could not test the maneuver flap configuration in the simulator, the team felt that this may be the best landing configuration since the incident pilot used maneuver flaps to successfully land his aircraft.

3. Turns were more controllable when control inputs were led with differential thrust.

4. It was not recommended that approaches be attempted in full flap configuration. However, it was felt by the test team that with full opposing rudder to the rudder hardover, a full flap approach could be attempted to minimize approach speeds, but with extreme caution.

5. When full flaps were used, Direct Lift Control (DLC) and speed brakes were not destabilizing. When using a large amount of differential thrust on the approach, DLC and speed brakes retracted, causing destabilizing pitch oscillations. This occurred when either throttle touched the MIL stop.

6. It was necessary to treat the bolter/waveoffs as though flying a single engine approach. Bolters attempted with both throttles simultaneously brought to MIL caused loss of control resulting in loss of the airplane with little or no opportunity to eject prior to water/flight deck impact.

7. It was determined that an attempt should be made to jettison drop tanks and all Air-to-Air/Air-to-Ground ordnance, but only if done symmetrically. An asymmetric load would cause greater degradation of lateral-directional stability and control.

8. Prior to touchdown, with little or no opposing rudder, the aircraft tended to develop a lateral drift due to the necessity to change throttle settings to control glideslope.

9. The aircraft did swerve upon touchdown in the simulator. The most recent incident aircraft swerved off the runway even during an arrested landing. The severity of the swerve aboard the ship could not be determined due to the previously discussed simulator limitations. Since the shipboard arresting gear has a much shorter runout and is self-centering, the swerve should be less severe than at the field.

10. The pilot was required to make a large number of lineup corrections in close during simulated approaches to the ship which may cause the tail hook to swing out to the side resulting in a potential for an increased number of bolters.

11. The pilot flew these approaches on the "front-side" of the power curve to minimize throttle motion which caused lateral oscillations. This may significantly change the attitude and could cause the tailhook not to engage the cross-deck pendent properly. This will increase the likelihood of the hook skipping the wire.

NATOPS EMERGENCY PROCEDURES

From the results gathered in the simulator, we were able to quickly develop NATOPS procedures for the fleet customer to use. These procedures permitted lifting the temporary "blue water ops" restriction. Simply put, they did not solve the Rudder Hardover problem, nor give the fleet procedures to land on the aircraft carrier with a rudder hardover. They just put NATOPS procedures in the fleet that had previously not been in place for a known failure mode. With NATOPS procedures in place and an increased fleetwide awareness of the problem, operational commanders are able to perform Operational Risk Assessments tailored to their operational environment. With the high fidelity the F-14 simulator provided, even without actual flight tests, the F-14 project team developed emergency procedures that were incorporated into the F-14 NATOPS Flight Manual. The procedures focused on the first and foremost consideration: was the aircraft controllable? The F-14 aircrew was then led through a logical sequence of steps, annotated at appropriate points with safety-of-flight lessons learned during the simulator sessions. This led to the recommendation to divert to a shore-based field or, if necessary, and if the pilot felt it was feasible, to attempt a carrier-based arrested landing. No barricade arrestment should be attempted aboard ship since the barricade gear is not self-centering. Adherence to these procedures will maximize the potential for a safe shore-based or ship board landing.

INCORPORATION INTO THE FLEET F-14 TRAINERS

The rudder hardover malfunctions were then implemented into the fleet F-14 Operational Flight Trainers (OFT's) - Devices 2F95A. The malfunction models are identical to those that reside at MFS. The flight fidelity was determined to be similar to that noted at MFS. Implementation is also planned for both the F-14B and F-14D trainer suites. Fleet F-14 pilots are currently training with these new malfunctions. Only 2 1/2 months elapsed between the most recent incident and the ready-for-training milestone in the F-14 OFT's.

CONCLUSION

This paper has presented a highly successful test effort for a situation where information and procedures that would normally be derived from flight test were successfully derived from a combination of analysis and simulation. Many insightful conclusions were drawn about the handling qualities of the F-14 using the simulator, even with the previously mentioned limitations. The level of confidence that one gains from using the simulator to "experiment" with different failure modes is high, assuming one recognizes the limitations of the simulator. While not the actual aircraft, it is felt that the fidelity was sufficient that all data compiled could lead to accurate recommendations for the fleet user. It is important to note that the team avoided making recommendations in areas where the simulation model was lacking. While perhaps not the preferred method of obtaining data to make recommendations, the high risk, lengthy schedule, and prohibitive cost made the simulator the only tool available to the team. As of this writing, no further incidents of rudder hardovers have occurred in the F-14 fleet. However, the understanding of the flying qualities and the ramification of pilot actions, all investigated in the simulator, may save an aircraft and an aircrew in the future.